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ROLLING ELEMENT SLIP RINGS FOR VACUUM APPLICATION

by Edward J. Devine

Goddard Space Flight Center
Greenbelt, Maryland

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SUMMARY

Electrical slip rings employing rolling contact elements (balls and raceways) were tested in a hard vacuum environment. Low noise operation was achieved at speeds up to 5000 rpm. Slip rings lubricated with MoS_2 operated with lower noise and had a longer life than slip rings employing solid metal film lubrication. Noise generated by rolling slip rings is more severe in air than in a hard vacuum. A technique was developed which operated satisfactorily in air for a time sufficient for preflight testing. A method of replenishing MoS_2 lubrication on the slip rings was devised. The final configuration operated in a vacuum of 2×10^{-9} torr at 2000 rpm for over 100 million revolutions at a noise level of 0.002 ohm rms.

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INTRODUCTION

This study investigated the feasibility of rolling contact electrical slip rings in a hard vacuum environment. Conventional sliding slip rings have been reasonably satisfactory in air, but are subject to problems in a hard vacuum environment. Conventional graphite brushes are unsatisfactory and metal wipers are suspect because of increased friction, greater wear, and the possibility of cold welding. Considerable research is underway on lubricants and materials to alleviate friction and wear. Although progress has and will continue to be made, it is evident that sliding contact elements will have definite limitations on speed and operating life.

It was surmised that friction and wear might be drastically reduced by replacing the conventional sliding slip rings with rolling contact elements. Accordingly, a limited study was conducted to investigate this approach.

APPROACH

Rolling elements have been used in the past for the transfer of electrical energy. Early dc motors employed rolling metal brushes. On occasion, the ball bearings of machines have been used to provide electrical contact between the rotor and stator. These methods are seldom used in a normal atmosphere because there is no wiping action and as a result oxide films and contaminants form which deteriorate the contact. This usually leads to arcing which quickly pits and destroys the rolling elements and races.

In a hard vacuum, two factors result in a favorable environment for rolling contact:

1. Surfaces are cleaned by outgassing and film formation is reduced.
2. Below a critical pressure, arcing is extinguished and damage from this source is eliminated.

Rolling contact slip rings can be used in many configurations. For this investigation, a thrust type of ball bearing configuration was selected (Figure 1).

The following features make this arrangement suitable for a basic study of rolling contact:

1. The contact load is uniform on each ball.
2. The contact load may be simply and accurately controlled.
3. Since the balls contact each race at the same diameter, nearly pure rolling action is achieved.
4. High quality commercial balls and races can be readily obtained.

TEST FIXTURE

The test fixture is shown in Figures 2 and 3. Two pairs of slip rings are employed in series to permit transfer of a signal to and from the rotating

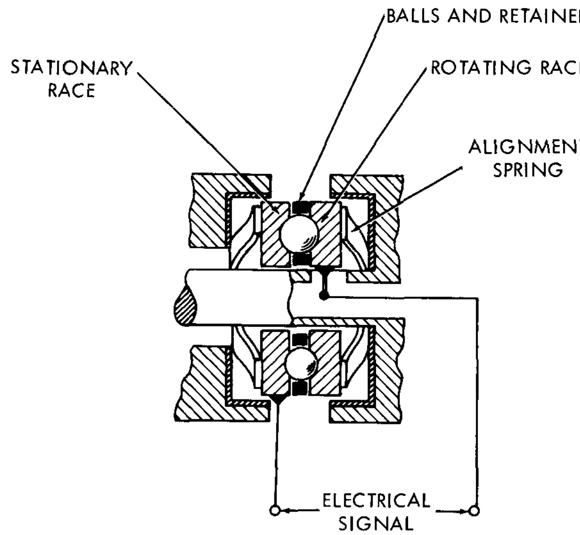

Figure 1—Basic rolling element slip ring.

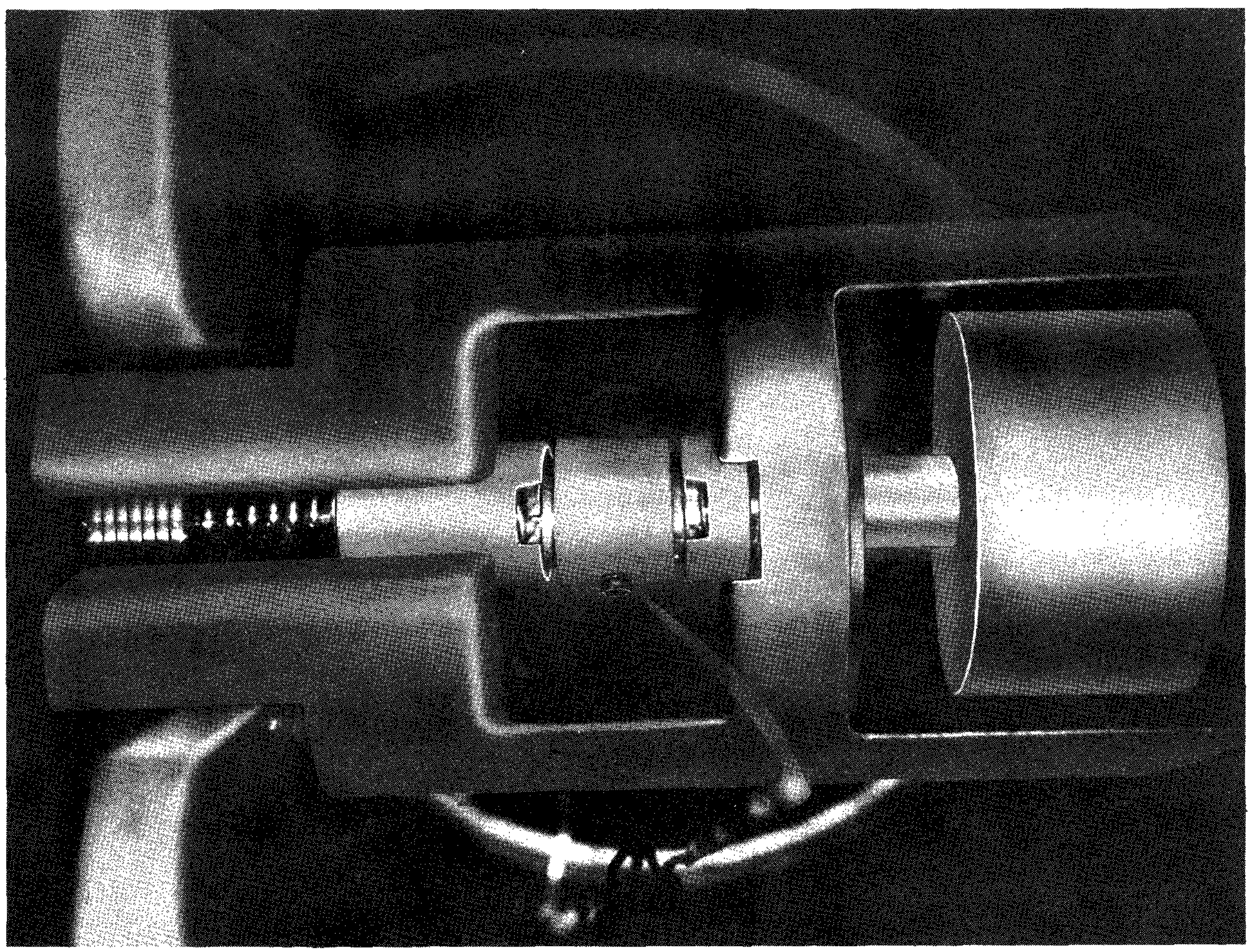

Figure 2—Slip ring test fixture.

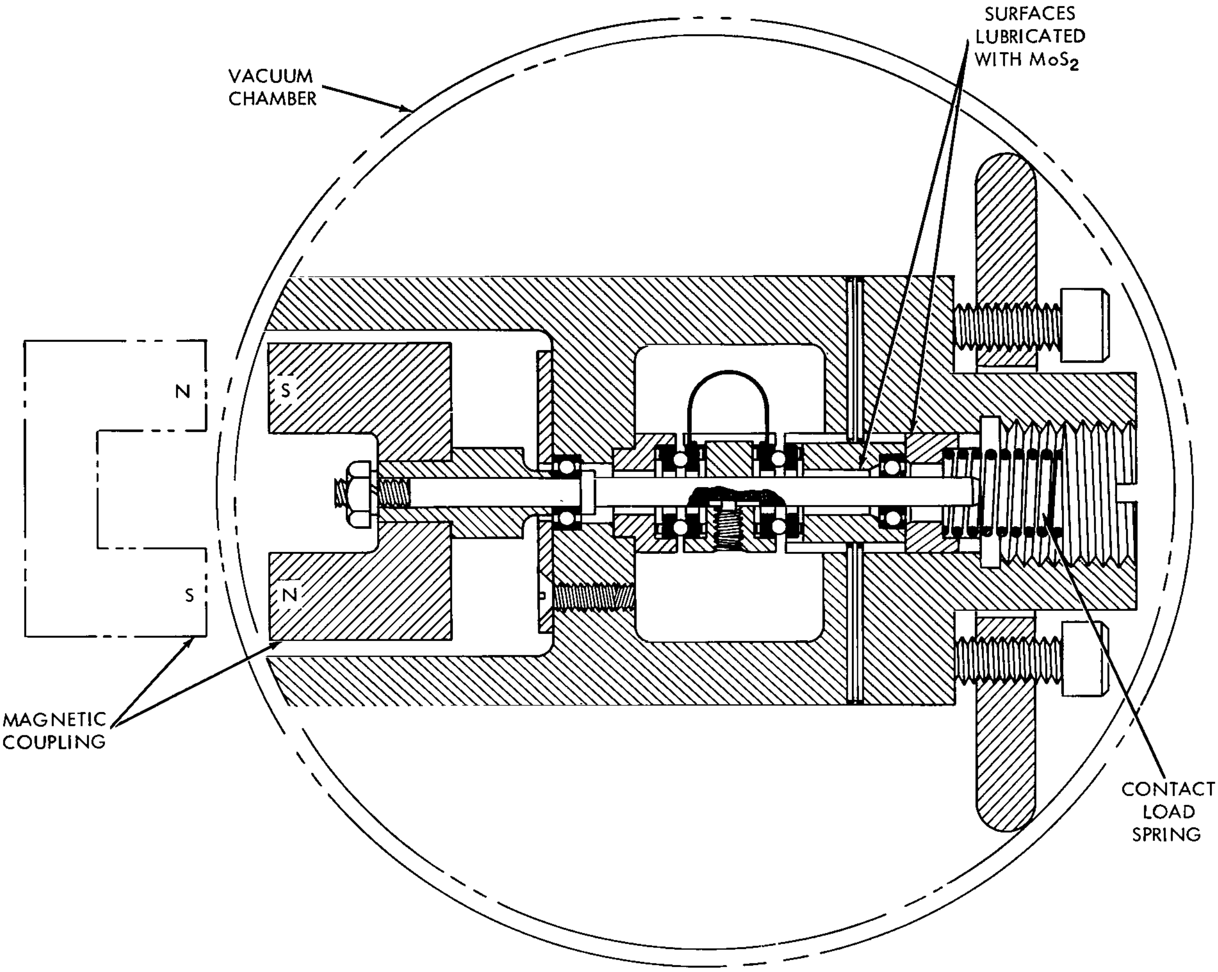

Figure 3—Slip ring test fixture assembly.

frame. Load is applied to the slip rings by means of a calibrated spring which forces on the rear bearing support. The rotating races are driven by a rotor which is keyed to the shaft. The rear bearing support and rotor are lubricated with MoS_2 to assure free motion and uniform loading on the front and rear slip rings. The radial support bearings are gold plated, and they are lubricated with MoS_2 applied in an alcohol slurry. A magnetic coupling capable of 0.87 in.-oz. slip torque drives the assembly through the wall of the vacuum chamber.

Extremely low outgassing of the entire fixture was achieved by complete elimination of organic materials. The slip rings are electrically insulated by a spray coating of aluminum oxide ceramic on the bearing seats. This material is an excellent insulator and can be honed to precision dimensions. Experience showed that a minimum spray coating of 0.010" was required for proper fabrication.

One requirement for low contact noise is uniform loading on the slip rings as they are rotated. The initial design attempted to achieve this by accurate (parallel) machining of the seating surfaces. However, tests established that a self-aligning feature was required to assure uniform contact pressure. A simple and effective method was provided by annular wavy spring washers behind one or both races of the slip ring.

More uniform contact was achieved with a loose radial fit (0.004") on the slip ring races rather than a close fit with extremely close tolerances on concentricity.

To facilitate assembly of the test slip rings, electrical connection was originally made by pressure contact with a gold-plated washer under the alignment spring washer. These additional contacts proved to be a source of noise. The problem was eliminated by resistance welding of the electrical connections directly to the edges of the slip ring races.

It was found that a contact load of 1 lb was sufficient to maintain continuous contact in the final test fixture. This load was maintained constant throughout all tests. This load probably could be reduced without a sacrifice in performance, but the lower limit was not experimentally determined.

EQUIPMENT

The vacuum facility employed was a stainless steel chamber with a 75 liter per second Vac-Ion pump (Figure 4). No mechanical forepumping or other source of oil contamination was present.

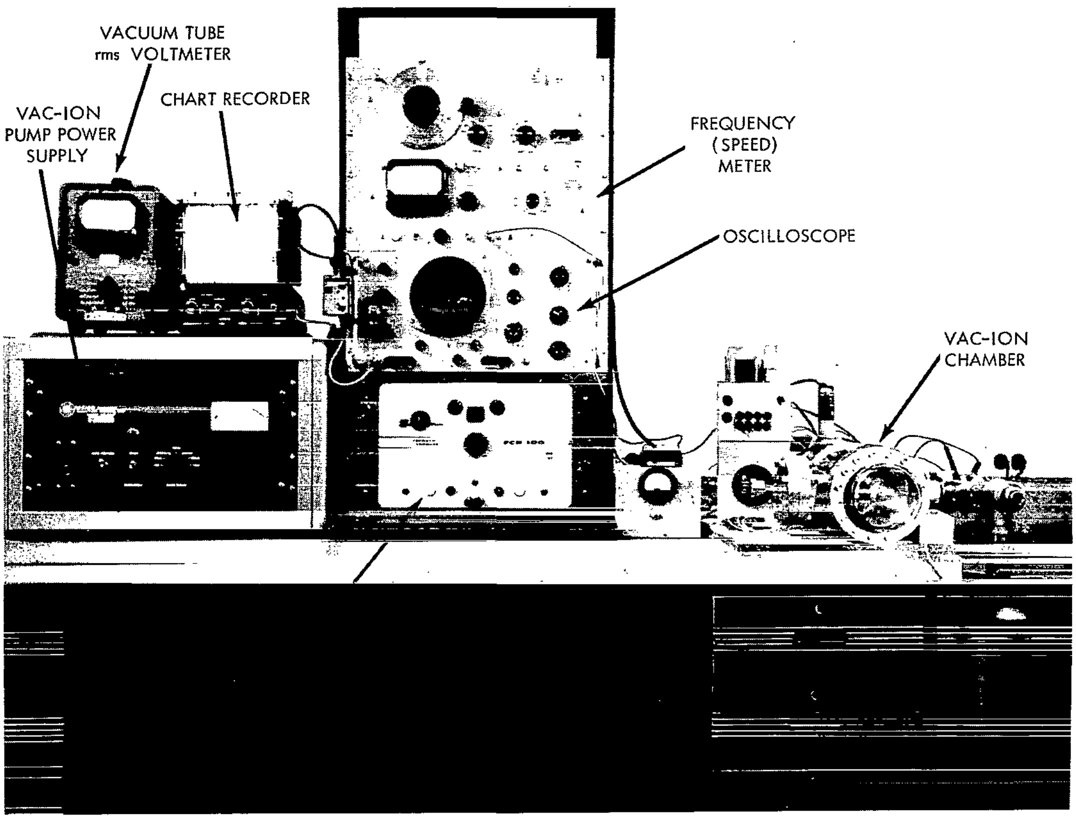

Figure 4—Test Equipment

Rotary drive for the experiment was provided by a 400 cps induction motor which was capable of 600 to 5000 rpm directly coupled (60-500 rpm with a 10 to 1 gear reduction). The motor was located outside the vacuum chamber and connected to the experiment by means of a magnetic coupling.

INSTRUMENTATION

The principal measurement made was contact noise. The circuit employed is shown in Figure 5. In all cases where noise is of an acceptable level, the contact resistance R_c is small compared with R_1, resulting in essentially constant current conditions. Contact noise is found by measuring the variations in voltage drop across R_c. This will be reported as peak-to-peak and rms voltage (E_n) at a given current and also as contact resistance variation calculated from:

$$R_n = \frac{E_n}{I}$$

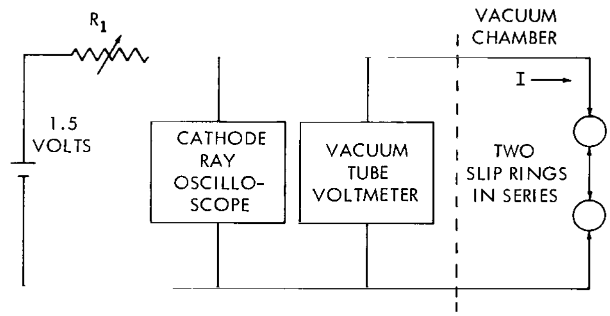

Figure 5—Circuit diagram.

All noise readings will be reported as measured and apply to 2 slip rings in series. Peak-to-peak noise is thought to be independent of the number of contacts, whereas the rms values should be reduced by approximately a factor of 2 for a single slip ring.

The instruments employed were:

For Peak-to-Peak Noise

Cathode Ray Oscilloscope	Hewlett Packard Model – 130 BR
	Sensitivity – 1 mv/cm
	Bandwidth – dc to 300 kc

For rms Noise

ac Vacuum Tube Voltmeter	Hewlett Packard Model – 400 D
	Sensitivity – 1 mv rms full scale
	Bandwidth – 10 cps to 4 Mc

For Contact Resistance

Recording Voltmeter	Varian Model — B22A	
	Full span balancing time — 1 sec	

Background noise from the line voltage and nearby laboratory equipment was reduced to less than 0.0001 volts peak-to-peak by shielding.

TEST RESULTS

Four test runs were required before the final configuration of the test fixture was decided upon. Because of the changes in the mechanical configuration resulting from these tests, the data obtained are not of interest. The test results of interest are summarized in Table 1 and discussed below.

Test 1

This test employed only gold-plated 440C stainless steel slip ring elements without lubrication. Initial operation in air gave low noise. The noise level in vacuum was moderate, but became severe after a short time (2.4×10^6 revolutions). Upon exposure to air the contact resistance became very erratic, averaging about 0.6 ohms. It rose to 20 ohms after a day in the atmosphere. Examination revealed that the gold plating was badly worn. It is surmised that the stainless steel base metal was exposed and that a nonconducting oxide film formed.

Test 2

To explore the nature of the nonconducting film, the same balls and races were again subjected to a vacuum environment. With the slip rings rotating at 200 rpm, contact resistance and noise dropped dramatically with decreasing pressure. At a pressure of 2×10^{-7} torr, contact resistance had dropped to 0.5 ohm and noise was less than 0.05 ohm peak-to-peak. The assembly was then run continuously at 5000 rpm with the results shown in Table 1. The noise level was fairly low until a sudden increase after 44×10^6 revolutions (Figure 6).

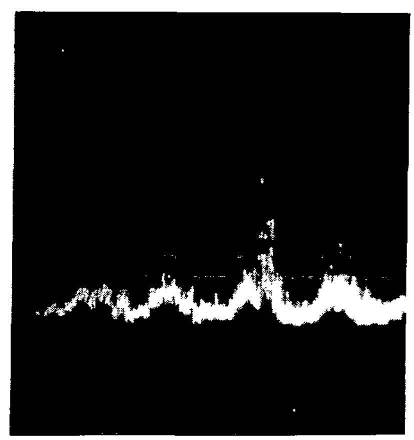

Figure 6—Noise trace for test 2, unlubricated gold-plated elements, 50 ma current, 5000 rpm; vertical scale—20 mv per grid division, horizontal scale—5 msec per grid division.

Test 3

It was clear that some additional lubrication was required both to reduce noise generated by "sticky" operation and to increase operating life. Ideally, the lubricant should be conductive and have extremely low vapor pressure. Liquid metals were considered, but they were not tested because of problems of corrosion and containment. Molybedenum disulphide was selected for testing despite the fact that in bulk it is an insulator. The MoS_2 was applied to gold-plated bearing elements

Table 1

Slip Ring Test Results

Test	Configuration: Balls	Races	Retainer	Lubricant	Air Operation: R_c (ohms)	p-p Noise (ohms)	Vacuum Operation: R_c (ohms)	p-p Noise (ohms)	rms Noise (ohms)	p-p Noise (mv at 10 ma)	Vacuum	Speed (rpm)	Life (rev $\times 10^6$)	Remarks
1	Gold-plated 440C	Gold-plated 440C	Gold-plated crown	None	0.095	0.010 (0 rpm)	0.56	0.6	0.02	6	1×10^{-7}	200	2.4	Noise increased to 140 mv p-p
2	See remarks				20.0	0.360 (0 rpm)	0.23	0.4	0.08	4	2×10^{-7}	5000	44.2	Noise increased to 1.5 volts p-p, configuration consisted of worn parts from test 1
3	Gold-plated 440C	Gold-plated 440C	Gold-plated crown	2 dips MoS_2	1.0	Very high	0.5	0.2	0.004	2	1×10^{-7}	5000	50.0	Failed mechanically
4	Gold-plated 440C	Gold-plated 440C	Gold-plated crown	2 dips MoS_2	2.0	2.0	0.3	0.03	0.002	0.3	5×10^{-8}	2000	16.0	Failed mechanically
5	Gold-plated 440C	Gold-plated 440C	Gold-plated crown	4 dips MoS_2	150.0	20.0	0.4	0.05	0.004	0.5	1×10^{-7}	2000	34.5	Failed mechanically; noise at 300 rpm, 20 mv p-p; relubricated assembly from test 4 was used
6	Tungsten-carbide	Rhodium-plated 440C	Gold-plated crown	None	—	30.0	—	60.0	—	600.0	2×10^{-7}	600	0.003	Failed mechanically
7	Tungsten-carbide	Gold-plated 440C	Gold-plated crown	None	100.0	40.0	0.3	20.0	—	200.0	4×10^{-6}	2000	0.12	Failed mechanically
8	Tungsten-carbide	Rhodium-plated 440C	Gold-plated crown	None	4.5	0.6	—	0.04	0.002	0.4	3×10^{-7}	2000	0.24	Failed mechanically
9	Tungsten-carbide	Rhodium-plated 440C	Machined gold	None	—	—	—	0.03	—	0.3	1×10^{-8}	2000	31.6	Failed mechanically
10	Gold-plated 440C	Gold-plated 440C	Machined duroid	None	8	60.0	25	15.0	2.5	150.0	4×10^{-8}	2000	13.4 +	Still running, noise very high
11	440C	*in situ* MoS_2	Crown *in situ* MoS_2	*in situ* MoS_2	600	High	0.3	0.04	<0.002	0.4	1×10^{-7}	2000	57.5 ?	Failed mechanically, may have been due to support bearings
12	Gold-plated 440C	Gold-plated 440C	Machined, 85% gold 15% MoS	Very light MoS_2	0.25	0.1 (2000 rpm)	0.3	0.04	<0.002	0.4	5×10^{-9}	2000	115	Failed mechanically

by dipping them in an alcohol suspension. The initial resistance was 8000 ohms, but after a brief period of operation at 1000 rpm it dropped to 1 ohm. Electrical noise remained high when the fixture operated in air.

This assembly was tested in vacuum and operated with very low noise at 5000 rpm until mechanical binding occurred at 50×10^6 revolutions. Post-test examination revealed pitting of one set of balls (Figure 7), indicating a failure of the lubricating film and the resulting adhesive wear.

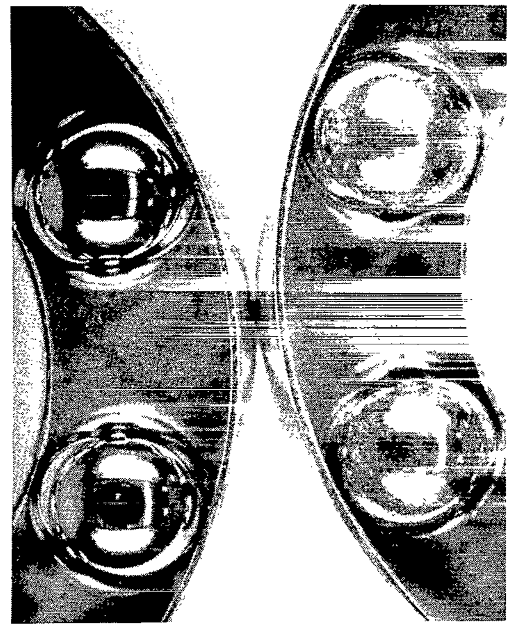

Figure 7—Balls and retainers from test 3. Note pitting on one set of balls.

Test 4

This test was a repeat of Test 3. Very low noise operation was noted before 16×10^6 revolutions when a sudden increase occurred.

Test 5

To determine if the failure in test 4 was due solely to a loss of lubricant, the assembly for test 4 was relubricated with MoS_2 applied in an alcohol suspension to the slip rings without disassembly or disturbance of the fixture. After relubrication, low noise operation resumed for an additional 34×10^6 revolutions.

Test 6

Other materials were investigated in an effort to find a combination which would have the desired characteristics of (1) low contact resistance; (2) low friction in vacuum; (3) good wear properties. Test 6 employed tungsten-carbide balls and rhodium-plated races. Contact resistance and noise in air were disappointingly high. Attempts to operate the combination in vacuum were not successful.

Test 7

This was a test of tungsten-carbide balls and gold-plated races and was also unsatisfactory.

Test 8

This test was conducted to determine whether the crown retainer (which is difficult to plate satisfactorily) was responsible for the failures in tests 6 and 7. The test was conducted with a machined gold retainer and results were not significantly better.

Test 9

This test employed tungsten-carbide balls, rhodium-plated races, and a machined retainer with MoS_2 lubrication. Very good vacuum results were noted until lubrication failure at 31×10^6 revolutions.

Test 10

This test employed gold-plated stainless steel balls and races and a machined duroid retainer. This combination operated very well mechanically, but with very high electrical noise.

The observations of contact resistance and noise reveal much about the nature of the lubricating film formed with the duroid material. An initial contact resistance of 1 ohm increased to practically open circuit after 1 hour of operation in air. Under vacuum conditions with 10 ma current, contact resistance dropped to 15-25 ohms. The much higher resistance of the duroid film in both air and vacuum when compared with MoS_2 films, clearly shows the presence of teflon in the lubricating film. This test was stopped after 31×10^6 revolutions because of continued high noise.

Test 11

The lubricant employed in this test is a coating of MoS_2 applied *in situ*. Stainless steel races and crown retainers were first electroplated with molybdenum which was then converted to MoS_2 by subjecting the specimen to H_2S gas at an elevated temperature and pressure. This process is described in detail in Reference 1. Balls were plain 440C stainless steel. This combination was noisy in air, but gave very good results in vacuum. The test was terminated after 54×10^6 revolutions because of mechanical difficulties. The slip ring components appeared to be in good condition (Figure 8) and it is suspected that failure was due to the support bearings.

Test 12

Previous tests showed that MoS_2 films and coatings are effective lubricants, but have limited life. In addition, MoS_2 films are electrically noisy in air, an undesirable limitation. It is believed that the best way to employ MoS_2 is in a continuous manner.

For this purpose a ball retainer was machined from a sintered compact 85 percent by weight gold and 15 percent MoS_2. Since the retainer was in continuous light sliding contact with the balls, a continuous transfer of MoS_2 was expected.

Assembly 12 employed gold-plated balls and races and the machined gold-MoS_2 retainer. When operation was attempted in vacuum, mechanical difficulties and high noise were experienced. Contrary to previous experience, it was evident that operation of unlubricated gold-plated elements is not satisfactory under a 1 lb contact load.

The balls and races were lubricated with a very light suspension of MoS_2 which was to serve until a film could be transferred from the retainer. It was found that this light film resulted in low noise operation in air. The test was then resumed in a vacuum of 5×10^{-9} torr. Contact resistance was 0.28 ohm and noise was less than 0.04 ohm peak-to-peak (Figure 9). A life of 115×10^{6} revolutions was achieved before mechanical failure.

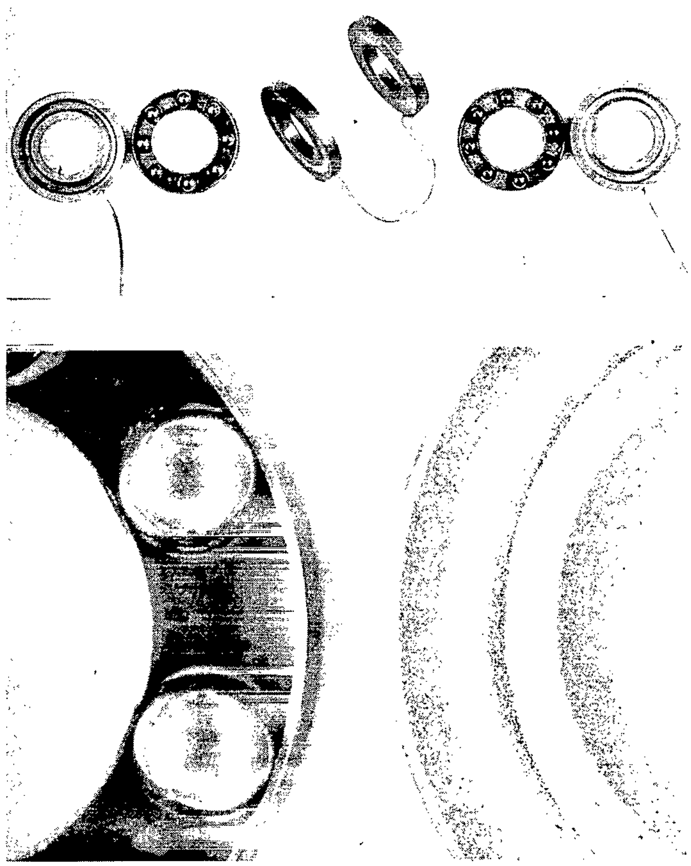

Figure 8—Balls, retainer, and race from test 11.

Miscellaneous Tests

Most of the noise measurements were made by observing the variation of low level dc signals. Long term tests were made with a constant 10 ma dc current through the slip rings. Spot checks were made at currents up to 100 ma and in all cases the voltage noise increased in an approximately linear fashion, indicating that R_n is constant over this range of current.

A brief test was made (test 9) at higher dc current (up to 1 ampere) in a vacuum of 2×10^{-7} torr. No visible arcing or damage to the slip rings resulted.

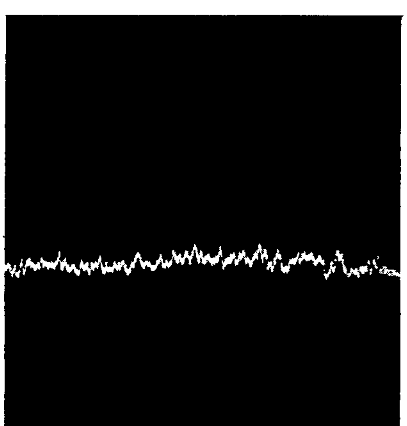

Figure 9—Noise trace for test 12, gold-MoS_2 retainers, 50 ma current, 2000 rpm; vertical scale-1 mv per grid division, horizontal scale-2 msec per grid division.

During test 3 a thermocouple output was connected through the slip rings which were run at 2500 and 5000 rpm in a vacuum of 3×10^{-8} torr. The accuracy and sensitivity of the potentiometer readings were not affected.

During test 12 an ac signal was transferred through the slip rings operating at 2000 rpm and 5×10^{-9} torr. The signal was varied from 1 to 20 kc at an amplitude of 100 mv peak-to-peak. No visible noise or distortion was observed.

CONCLUSIONS

It has been demonstrated that rolling contact can be employed for electrical signal transfer at low noise in an ultra-high vacuum environment. Contact noise can be less than 2 milliohm rms even at speeds up to 5000 rpm. There are indications that the higher the vacuum, the less will be the contact noise.

Lubrication is required for maximum performance from rolling contact slip rings. Precious metal platings without additional lubrication appear unsatisfactory because of high torque and "sticky" motion. The best results obtained to date have been with stainless steel balls and races, gold-plated and with a thin initial film of MoS_2. Continuous lubrication is provided by ball retainers (separators) machined from compacts with a high MoS_2 content.

A direct comparison of the performance of rolling and sliding contact is difficult because of the paucity of reported data and wide variation in test conditions and instrumentation methods.

Assuming a reasonable specification for high quality miniature sliding slip ring operating in air, we could expect:

Noise — 50 milliohms peak-to-peak, 5 milliohms rms.

Maximum speed — 200 rpm,

Maximum life — 20×10^6 revolutions.

Expected performance in vacuum is more difficult to predict. Reference 2 reports that satisfactory operation is not possible and recommends oil vapor lubrication. Reference 3 reports favorable results for brushes impregnated with MoS_2 at 17.8 rpm and a vacuum of 2×10^{-6} torr. Noise figures from Reference 3 are not directly comparable with the present data because of the low bandwidth (8 cps) reported.

No data are available on the performance of sliding contacts at the speeds and vacuum levels explored in this study. Based upon the data obtained in this study, it appears that rolling contact elements are capable of the following performance:

Noise — 50 milliohms peak-to-peak, 5 milliohm rms.

Maximum speed — greater than 5000 rpm,

Maximum life — greater than 100×10^6 revolutions.

Vacuum environment — 10^{-6} torr and lower.

(Manuscript received October 11, 1963)

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